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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

TRIM AND SINKAGE EFFECTS ON WAVE RESISTANCE

WITH SERIES 60, C_B=0.60

by

Yoon-Ho Kim

and

Douglas Jenkins

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SHIP PERFORMANCE DEPARTMENT

RESEARCH AND DEVELOPMENT REPORT

SEPTEMBER 1981

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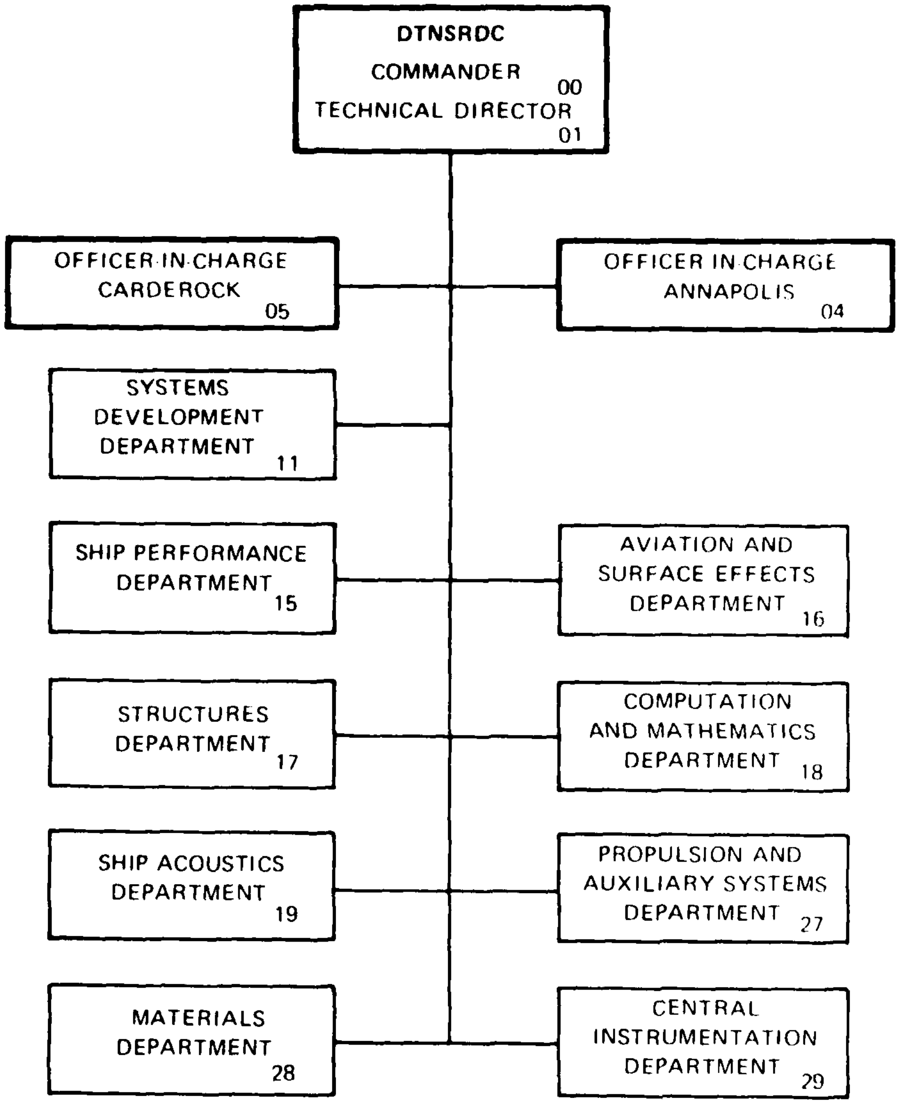

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Resistance experiments with Model Series 60, C_B=0.60 have been carried out with the model free to trim and sink and with the model fixed at zero trim and sinkage. The measurements include wave profiles along the hull, sinkage and trim, wave resistance, and total resistance. The difference in the measured values for the two experimental conditions is assessed and a comparison with calculated results is made. Discrepancies between the measured and the calculated values indicate that the linear potential-flow theory used for the calculations needs to be modified in order to predict the wave resistance, trim and sinkage, and wave

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profiles correctly.

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NOTATION

B	Beam at midship
C	Resistance coefficient, $C = \text{Resistance}/(\frac{1}{2}\rho U^2 S)$
	C_F: Frictional resistance coefficient
	C_{FORM}: Form drag coefficient
	C_R: Residual resistance coefficient
	C_T: Total resistance coefficient
	C_W: Wave resistance coefficient
C_B	Block coefficient, $C_B = \nabla/L_{pp}BH$
F_n	Froude number, $F_n = U/\sqrt{gL_{WL}}$
g	Gravitational acceleration
H	Draft
h	Sinkage, $-(\Delta Z_{bow} + \Delta Z_{stern})/2$; nondimensionalized by $U^2/2g$
K_p	Partial form factor
L_{pp}	Length between perpendiculars
L_{WL}	Load waterline length
R_e	Reynolds number, $R_e = UL_{WL}/\nu$
S	Wetted surface area of ship
S_o	Wetted surface area of ship at rest
U	Forward speed of ship or model
∇	Displaced volume
W	Waterplane area
ΔZ_{bow}	Vertical distance measured at bow from calmwater surface (positive above calmwater surface)
ΔZ_{stern}	Vertical distance measured at stern from calmwater surface

α	Trim(positive for bow down), $\alpha = -(\Delta Z_{bow} - \Delta Z_{stern})$; nondimensionalized by $U^2/2g$
ζ	Wave profile along hull, measured relative to the calmwater surface
ν	Kinematic viscosity, $\nu = 9.838 \times 10^{-7}\ m^2/sec.$ at 21^oC (fresh water)
ρ	Mass density, $\rho = 31.0\ kg/m^3$ at 21^oC (fresh water)

ABSTRACT

Resistance experiments with Model Series 60, C_B = 0.60 have been carried out with the model free to trim and sink and with the model fixed at zero trim and sinkage. The measurements include wave profiles along the hull, sinkage and trim, wave resistance, and total resistance. The difference in the measured values for the two experimental conditions is assessed and a comparison with calculated results is made. Discrepancies between the measured and the calculated values indicated that the linear potential-flow theory used for the calculations needs to be modified in order to predict the wave resistance, trim and sinkage, and wave profiles correctly.

ADMINISTRATIVE INFORMATION

This work was authorized by the Naval Material Command (08T23), and funded under the Ship Performance Task area 421-153, administered by the Ship Performance Department of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) with Work Unit Number 1507-101-66.

INTRODUCTION

There have been numerous efforts in the past not only to predict wave resistance analytically but also to measure it by experimental means. William Froude(1810-1879) seems to have been the first to appreciate fully the differing roles played by friction and wave making in ship resistance and the significance of this difference in trying to project data from model tests to full-scale size. His idea and analysis still form the basis of the prediction of resistance of ships by ship model testing. While Froude's efforts were confined to experimental methods, an analytical endeavor of predicting the wave-making resistance was made by Michell in 1898. Michell's theory which was based on the assumption of thinness of ships was the first consistent mathematical theory developed at that time. However, due to computational difficulties, progress has been rather slow. Presently, the advent of large computer facilities and rapid growth of new computational techniques permit us to make use of more general formulae available beyond thin ship theory.

Reflecting on increased activity in the field, a workshop on ship wave-resistance computation[1]* was held at the David W. Taylor Naval Ship R&D Center (DTNSRDC) in 1979. The objective of this meeting was to evaluate existing computational methods for predicting wave resistance. Significant discrepancies were found among computed values of wave resistance by what appears to be exactly the same method. Most of the calculations were made for a ship with a

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[1]References are listed on page 11.

fixed trim and sinkage, whereas the experimental data used for comparison were obtained from a model free to sink and trim. In order to provide a common data base for the evaluation of the calculated wave resistance values, it was decided to carry out a model experiment at DTNSRDC for both conditions. Model Series 60, C_B=0.60 was selected for the experiments to measure total resistance, wave-making resistance, sinkage and trim, and wave profiles along the ship hull over a range of Froude numbers. The results of this work are reported herein. The measured values are compared between the two experimental conditions and the effect of sinkage and trim is determined on the wave profiles, wave resistance and residual resistance. Comparisons are made between the calculated and experimental results. From among the papers presented at the Workshop, Dawson's computation[2] has been chosen to make the comparison. Dawson's paper presented the most complete set of calculations, providing an opportunity to compare the calculated values of not only wave resistance, but wave profiles and residual resistance as well.

In the following the model experiments are described, the theoretical calculations are outlined and the results of the comparison are shown.

MODEL EXPERIMENTS

Series 60, C_B=0.60 was chosen for this experiment. The model and its particulars are shown in Figure 1 and Tables 1 and 2. The model was made of wood, 6.1 m (20 ft) L_{pp} and 6.2 m (20.335 ft) L_{WL} and was towed in the deep water basin at DTNSRDC which has a cross section 15.54 m (51 ft) wide and 6.7 m (22 ft) deep. A trip wire 0.61 mm (0.024 inch) in diameter was provided for turbulence stimulation at model station 1 and was attached along a line parallel to the bow profile by staples. A floating girder was used for measuring the total resistance, and a force block gauge was used simultaneously for the model free to trim and sink. The trim and sinkage were measured by potentiometers located at the FP and AP of the model. The wave profiles were marked at every station along the hull with a grease pencil during the run and were read after each run. Note that since the wave profiles were measured relative to the undisturbed free surface, the sinkage was included in the wave-profile measurement for the free model condition. The model was towed over the Froude number range of 0.15 to 0.35, concentrating on the following six Froude numbers: 0.22, 0.25, 0.28, 0.30, 0.32 and 0.35. These values were recommended by the Workshop on Ship Wave-Resistance Computation.[1]

NUMERICAL METHOD

Among available numerical results, Dawson's computation[2] has been chosen to make comparisons. This does not necessarily mean that his method is superior to others, but rather the choice was based on the advantages that his data were more thorough than others, providing results not only for wave resistance, but wave profiles and residual resistance as well. His computer code was also easily accessible. Incidentally among the results presented at the Workshop[1], Gadd's prediction of wave resistance shows the most favorable agreement with the measured values for this particular model.

Dawson solved a linearized free-surface problem but satisfied the exact hull boundary conditions. He used a fundamental singularity (Rankine source) distribution method. Simple sources were distributed over both body surface and a local portion of the undisturbed free surface. The body and free surfaces were approximated by a large number of elements. Each element was quadrilateral and was treated as a source patch with constant strength. The detailed description of the method can be found in Reference 2. In the following some of Dawson's input data, computing time, and other information are provided for user's comparisons:

Computer used: TI-ASC (Texas Instrument Advanced Scientific Computer) at the Naval Research Laboratory (NRL).

Number of elements on the body surface: 208 (26x8)

Number of elements on the undisturbed free surface: 360 (36x10)

CP(Central Processor) time for the first Froude number: 240 sec.
additional Froude number: 120 sec.

Central memory size required: 300K

Output: Wave profile, sinkage and trim, wave resistance and residual resistance.

Note that because of symmetry, only half of the body and free surfaces were actually used.

RESULTS

The measured wave profile along the hull, sinkage and trim, the wave resistance and the residual resistance at various Froude numbers are presented here along with the numerical predictions. All of the data are shown in figures, and tables of the results are also provided for completeness.

To facilitate comparison, the following non-dimensionalizations are made:

$$\text{Wave profile } (\bar{\zeta}) = \zeta/(U^2/2g) \tag{1}$$

$$\text{Trim } (\alpha) = -(\Delta Z_{bow} - \Delta Z_{stern})/(U^2/2g) \tag{2}$$

$$\text{Sinkage } (h) = -(\Delta Z_{bow} + \Delta Z_{stern})/(U^2/g) \tag{3}$$

$$\text{Resistance coefficient} = \text{Resistance}/(\tfrac{1}{2}\rho g U^2 S) \tag{4}$$

where U is the forward speed of the model, g the gravitational acceleration, ΔZ_{bow} and ΔZ_{stern} the vertical distance of DWL (designed waterline) measured respectively at the bow and the stern from the calm water surface, ρ the water density, and S the wetted surface area of the model. The sinkage and trim are considered in the wetted surface area calculation for a model free to sink and trim, but the change due to the wave profile is not included.

It should be pointed out that our model is slightly different from that of Huang et al.[3] In their experiment a hull modification aft of station 18 (while preserving the same sectional area) was made to accommodate a propeller shaft used for propulsion and vibration experiments.

A. WAVE PROFILE

Photographs of wave profiles at six different Froude numbers are shown in Figures 2 and 3 for "model fixed" and for "model free to trim and sink", respectively and the wave profiles for all six Froude numbers are plotted together in Figure 4 for the model fixed and in Figure 5 for the model free by using the actual model scale. In Figure 6, a set of observed wave profiles are reproduced for both cases and are compared with Dawson's prediction for the free model condition (except for $F_n = 0.22$). The measured wave profiles show that the phases are almost the same for both cases throughout the Froude number range, but the wave profile for the model fixed is always slightly higher than that for the model free to trim and sink. The forward half of the calculated wave profiles compare favorably with the measured

ones, but the agreement becomes poorer downstream. The prediction always overestimates the magnitude of the last crest, and the phases also shift slightly for the after half of the body. The discrepancy near the stern may be explained partially by the fact that the thick growth of boundary layer violates the underlying assumption of potential flow and the oddness of body geometry near the stern causes computational difficulties (this part will be discussed later in detail). In order to improve the prediction, not only the non-linear free-surface condition but also the viscous effects should be taken into account. Note that Dawson's wave profile were taken from the surface elevation at the panels next to the body, not on the actual body surface. Overall, the difference in wave profiles between the model fixed and the model free doesn't seem to be as great as that of the wave resistance (to be discussed later). The measured values of wave profile are presented in Tables 3 and 4.

B. SINKAGE AND TRIM

The measured sinkage and trim are also compared with numerical prediction. Dawson determined sinkage and trim by computing the flow with the ship fixed and then determining the vertical hydrodynamic force and trim moment. The amount of sinkage and trim needed to balance the hydrodynamic force and moment are computed. In Figure 7 are shown comparisons of the measured and the calculated sinkage and trim. The agreement seems fairly good for the sinkage curve, but the trim curve displays discrepancy, especially at low Froude numbers. It is noted that for the model the sinkage and trim are relatively small and do not vary much within the chosen Froude number range. This explains why the wave resistance curves shown in Figure 8 are not much different between the two different experimental conditions. The measured values of sinkage and trim are presented in Table 5.

C. WAVE RESISTANCE

Wave resistance can not be obtained directly from the measured total model resistance. However, Eggers (1962, 1963)[4] has shown for an ideal fluid that wave resistance may be calculated from wave profile measurements alone. There are two versions of the method: transverse profile measurements and longitudinal-profile measurements. The longitudinal-profile measurement was adopted for these experiments. This measurement can be achieved rather easily in a model experiment, by locating a stationary wave probe at some suitable point in the towing tank and taking a time dependent record as the model passes by.

The location of the wave probe for these experiments was 2.3 meters off the centerplane of the model, on the port side. The computer program used for the computation of C_W has been reported by Reed (1979)[5]. A fundamental limitation of this method, of course, is that the wave data used for the analysis should be taken in the region where the wave pattern is essentially unaffected by reflection. In fact the reflection of the bow wave from the tank wall is so easily distinguishable in the wave records that this does not cause any difficulty in the data analysis. One has to be reminded that the wave resistance obtained by this method implicitly contains viscous effects. Figure 8 shows wave-resistance curves for the model fixed and for the model free. In order to avoid possible errors in the experiment, at least 4 runs were made at each of the six Froude number values recommended by the Workshop.

At small Froude numbers (F_n<0.28) the wave resistance measured for both conditions shows almost identical values, whereas Dawson's calculations result in a substantial difference. For the model fixed, Dawson's prediction tends to follow the experimental curve throughout the Froude number range, but the predicted magnitudes are considerably smaller than the measured ones. For the model free to trim and sink, his calculation shows larger values than the measured ones in the range $0.28<F_n<0.32$.

D. RESIDUAL RESISTANCE

The residual resistance coefficient, C_R, is defined as the difference between the total resistance coefficient, C_T, measured, and the frictional resistance coefficient, C_F, acting on a flat plate of the same wetted-surface area as that of the ship at rest. Hence the residual resistance includes wave resistance, form drag, and effect of trim and sinkage. The residual resistance results are shown in Figure 9. One of the most interesting aspects of these curves is that the hollows which appear in the wave resistance obtained by the longitudinal wave-profile method (see Figure 8) at about Froude numbers 0.24 and 0.32 are smoothed out in Figure 9 for both the fixed model and the free model conditions.

E. FORM DRAG

In order to improve the method of extrapolating the resistance measurement of model tests to full-scale condition, several efforts have been made in using a hull "Form Drag" component. The form-drag coefficient is commonly expressed as

$$C_{FORM} = a+bC_F \tag{5}$$

where a and b are empirical coefficients depending upon the hull form and C_F the ITTC(1957) correlation line. In Figure 10 form-drag coefficients C_{FORM} are plotted. The measured values are simply obtained by subtracting C_W from C_R. Here again the large differences in C_{FORM} between the two experimental conditions are observed. These differences are directly related to the residual resistance. Because there is only a small difference in C_W between two conditions, most of the difference in C_R comes from the form drag.

Dawson modified Equation (5) and used the following simple formula for this model:

$$C_{FORM} = \{(1+2K_p)S/S_o - 1\} C_F \tag{6}$$

where K_p is the partial form factor, S/S_o the ratio of the wetted surface with trim and sinkage to the wetted surface with the ship at rest. The computed values using Equation (6) are shown in Figure 10. The measured values are always slightly greater than the computed ones for this particular model, but considering the simplicity of the formula, these values are acceptable.

The various resistance components obtained from the experiment are shown in Tables 6 and 7.

DISCUSSION

Sinkage defined in Equation (3) shows positive values for all Froude numbers considered (see Figure 7). This indicates that the actual displaced volume of a model free to trim and sink is always slightly larger than that of a model fixed and consequently the resistance of a free model is expected to be larger than that of a fixed one.

Sinkage and trim are obtained by solving two simultaneous equations a force and a moment equation. Sinkage is more directly related to vertical force and trim to pitch moment. All the sinkage results presented at the Workshop show fairly good agreement with the present experimental values, whereas the trim results do not.

If we presume that the centroid of waterplane is zero, in other words the centroid of waterplane coincides with the origin of coordinate system which is usually taken at the midship of a ship, sinkage h is obtained directly from vertical-force balance alone, i.e.,

$$\rho gWh = \text{surface integral of hydrodynamic pressure in vertical direction,}$$

where W is the waterplane area. For an ordinary ship, the centroid of the waterplane is close to the midship and hence sinkage largely depends on the pressure integral, whereas trim is very sensitive to the longitudinal pressure distribution. Without predicting both trim and sinkage correctly, one should not anticipate any good numerical results of wave resistance which depends more sensitively on the pressure distribution along the ship hull, particularly near the bow and stern parts. In Figure 11, the sinkage at the bow and stern, ΔZ_{bow} and ΔZ_{stern}, are presented. These curves clearly demonstrate that the theory is less reliable in predicting the local sinkage, although the predicted sinkage at the centroid of the waterplane is in excellent agreement with the experimental results as shown in Figure 7.

It is interesting to note that the differences between the measured and the calculated sinkage, trim and wave profiles are relatively small, but as shown in Figure 8 the discrepancy in wave resistance between theory and experiment is much greater than expected. This could be partially explained by quoting Wehausen's lecture notes (even though his remarks were made on thin-ship theory): "It is reasonable to ask why the agreement between theory and experiment is so much more satisfactory for wave profiles and trim and sinkage than resistance. The reason lies in the fact that in computing the resistance the pressure is multiplied by the x-component of the normal and then integrated, whereas in sinkage and trim it is the y-component* that plays the most important role. The x-component will be of opposite signs at the two ends of the ship and almost zero in between. Whereas the y-component is of one sign over the whole length. Consequently, the resistance will be the difference of two large numbers whereas the sinkage will be the sum. For the wave profile this integral of the pressure isn't required, so that the inaccuracy associated with taking the difference of large numbers doesn't arise."

Figures 8 and 9 show that the difference in C_R between two experimental conditions is much greater than that in C_W. This implies that a small change in

*Vertical component.

sinkage and trim doesn't effect the wave resistance significantly but it does effect the residual resistance.

Discrepancies found in wave resistance, sinkage and trim between theory and experiment indicate a definite need for improvement of the theoretical predictions. Most of the contribution to the wave resistance comes from the difference between the pressure integral at the bow and stern and particularly these two parts seem to most possibly violate the underlying assumptions for linear potential-flow theory. Dawson used a linearized free-surface condition but satisfied the exact shiphull boundary condition in his computation. Assuming that there are no errors in his computation (numerical accuracy will be discussed next), then we have to solve the nonlinear free-surface problem and/or to include the viscous term to predict wave resistance correctly.

Quadrilateral patch is the basic element and constant strength is assumed over the source patch in Dawson's computation. Several disadvantages using quadrilateral patch and constant source strength were pointed out by Webster (1975)[6]. Among them are: it is not possible to arrange the trapezoids so that all four corners of each element match the corners of adjacent elements; the source distribution is discontinuous at the boundary of two elements. For better resolution, of course, the body and the free surfaces should be approximated by more fine elements, but because of the computer-core limit and the drastic increase of computing time, one has to compromise between numerical accuracy and computer cost.

Dawson considered sinkage and trim effect on wave resistance but neglected the change of wetted surface due to wave profile. Contribution of the change of wetted surface due to wave profile to wave resistance is not yet known and will be worth investigating in the future. If one includes sinkage and trim effect in his calculation, the change of wetted surface must be considered simultaneously because they are of the same order.

Residual resistances measured by Todd[7] and Huang et al.[3] and the present experiments are plotted together in Figure 12 and are presented in Table 8. Todd's results and the present experiments show almost identical measured values for $F_n \leq 0.28$ but Todd's measured values are slightly greater than the present ones for $0.29<F_n<0.32$. Huang et al.'s data are less than the others. It is suspected that the difference is the direct consequence of the hull modification made aft of station 18 for their propulsion and vibration test.

CONCLUSIONS

In comparing the experimental results and the theoretical predictions, the following can be concluded:

1. The measured wave profiles for the fixed model are slightly greater than those for the free model, but the phases are almost the same. The prediction always overestimates the magnitude of the last crest measured and the phases also shift after half of the body.
2. Residual resistance of the free model is greater than that of the fixed model.
3. C_W curves show slight hump and hollows for both conditions, but the C_R curves are smooth.
4. The difference of C_R between the free and fixed conditions is much greater than that of C_W.
5. Sinkage and trim effect is significant on C_R and C_{FORM}, but not on C_W.
6. If sinkage and trim are considered in wave resistance calculations, then the change of wetted surface must be considered because they are of the same order.

Within the limits of the present study, we found that the linear potential-flow theory does not provide us with reliable predictions for a realistic hull form. The difficulty arises from the fact that it is the near field which must be predicted correctly in order to know the wave resistance and the near field, especially near bow and stern, is the place where various non-linear phenomena occur. The importance of the second-order effects on wave resistance had been proved by both theory and experiment for the two-dimensional case[8] and this may be also true for the three-dimensional case.

ACKNOWLEDGMENT

The authors are grateful to Dr. Choung M. Lee and Dr. W.-C. Lin for their invaluable suggestions and helpful discussions.

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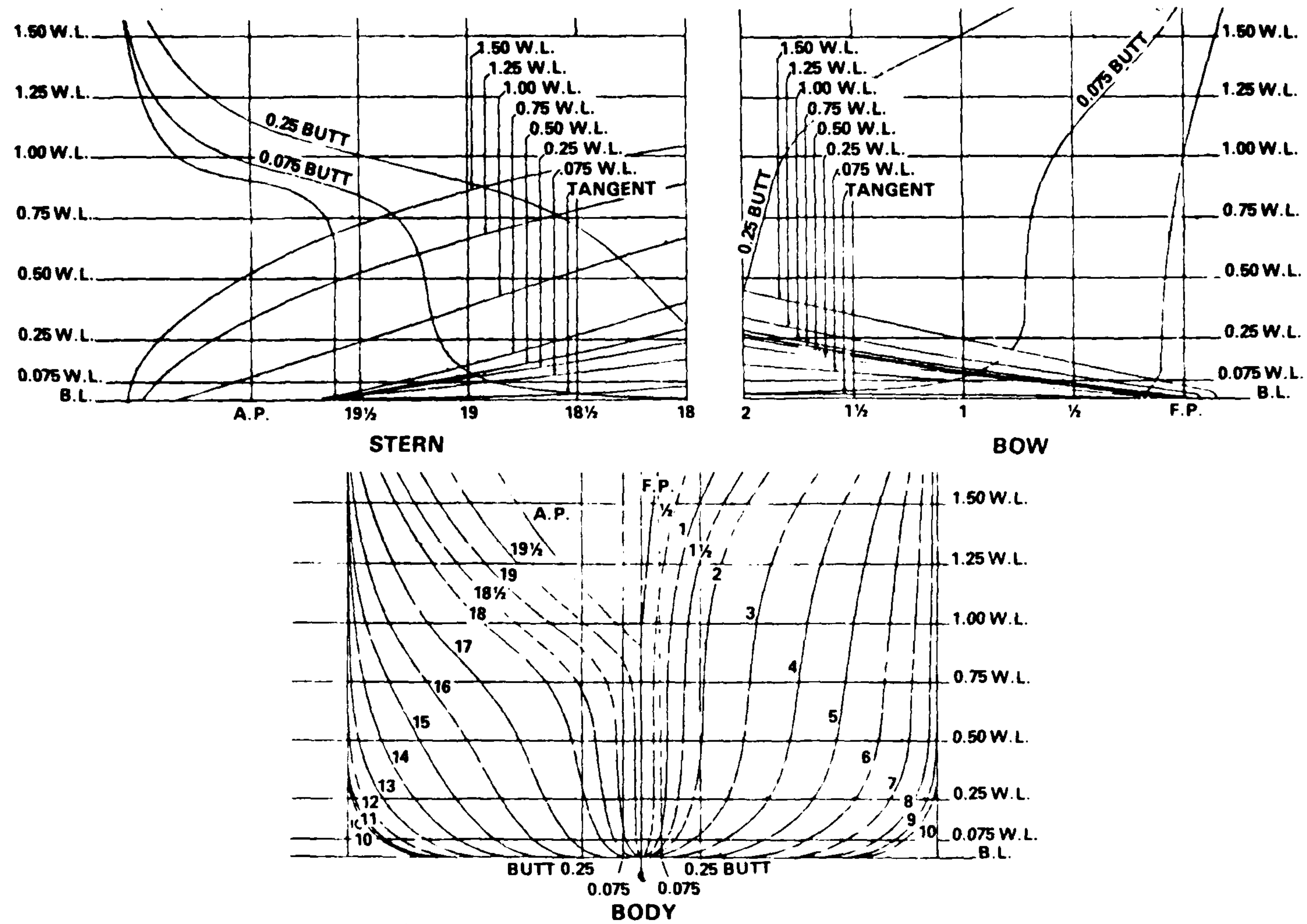

Figure 1 — Lines of Series 60, $C_B = 0.60$ (from Todd, 1953)

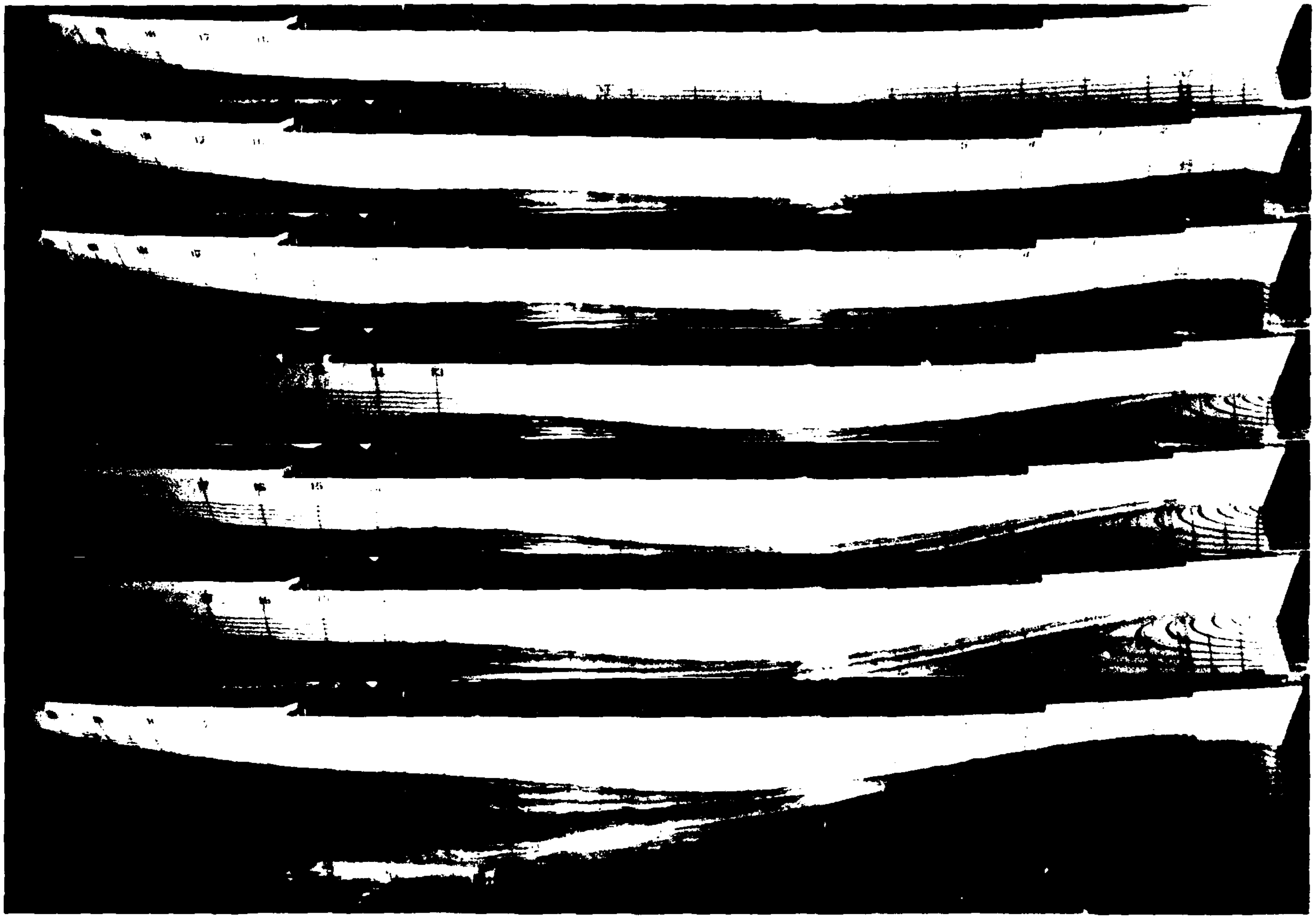

Figure 2 - Wave Profiles with Model Fixed

Fn=.00

Fn=.22

Fn=.25

Fn=.28

Fn=.30

Fn=.32

Fn=.35

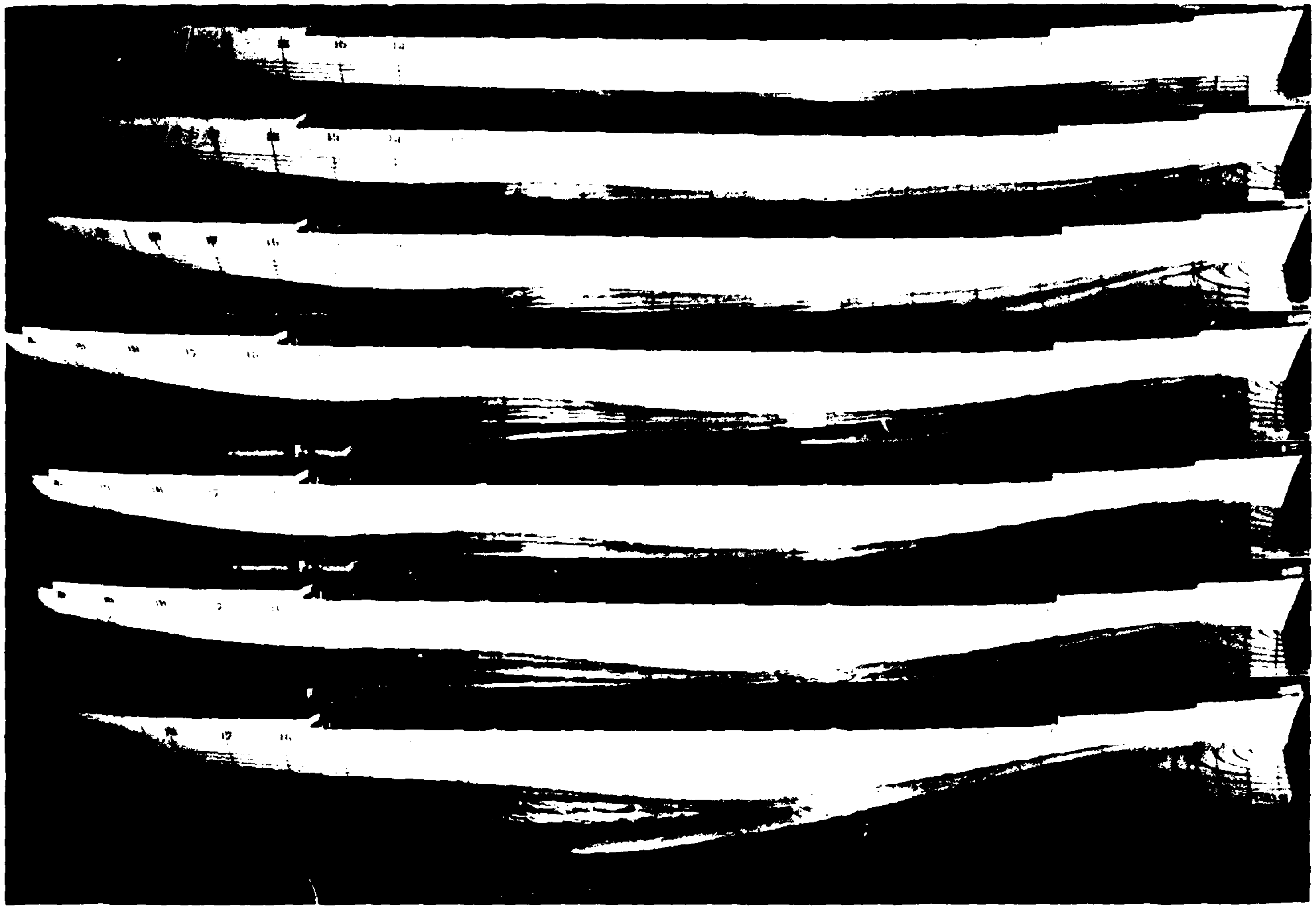

Figure 3 - Wave Profiles for Model Free to Trim and Sink

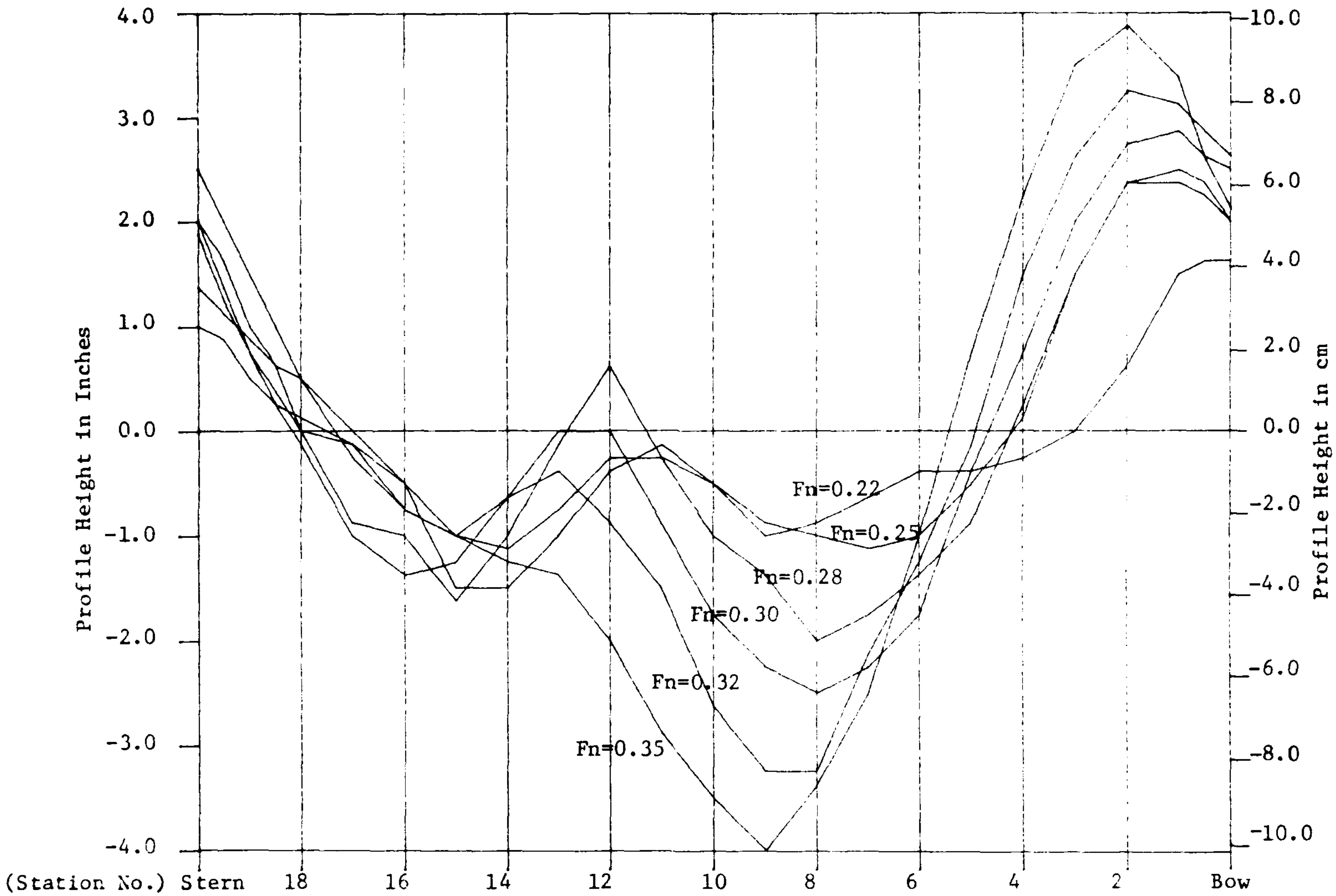

Figure 4 - Wave Profiles Observed for Series 60, C_B=0.60 with Model Fixed

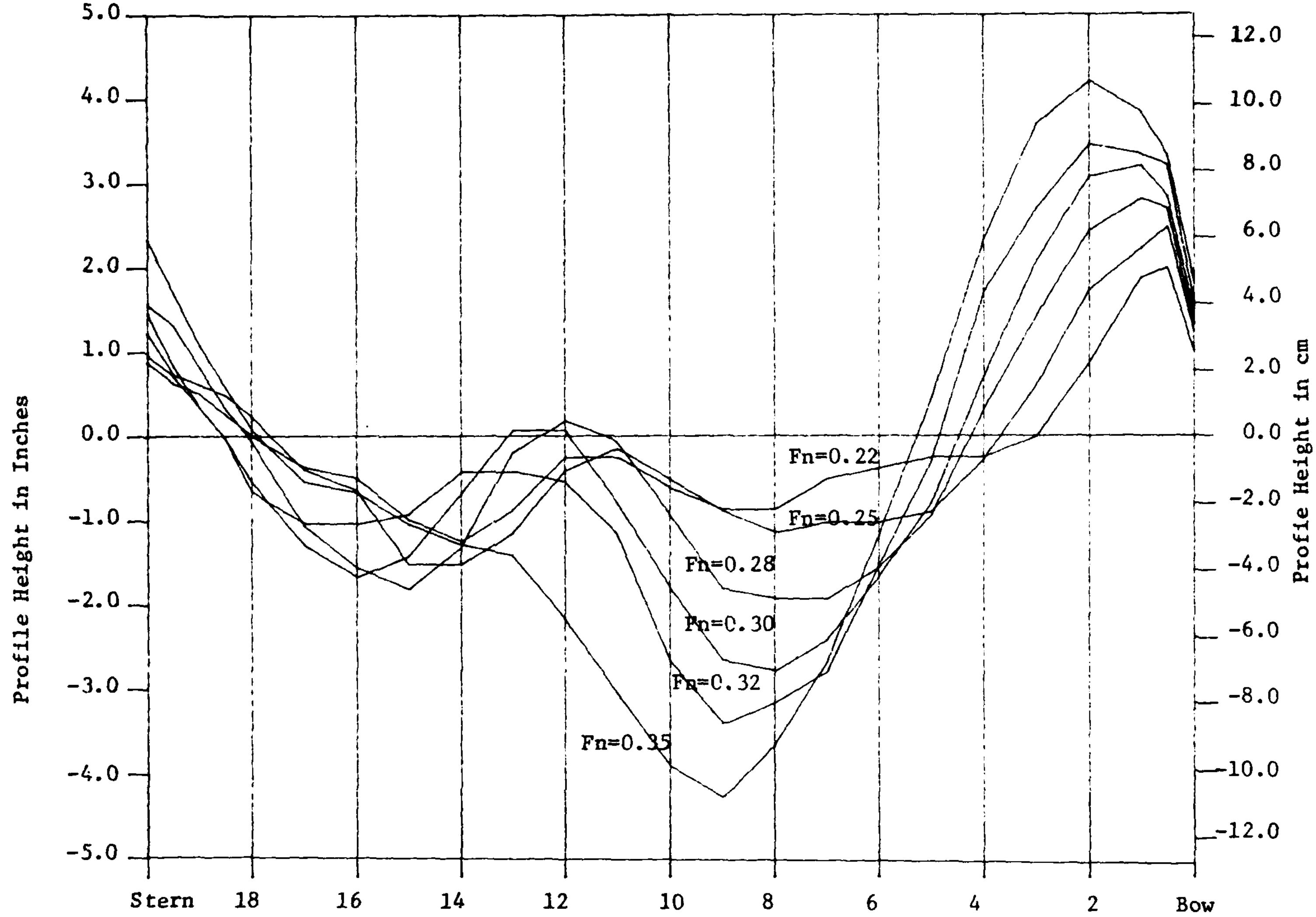

Figure 5 - Wave Profiles Observed for Series 60,C_B=0.60 with Model Free to Trim and Sink

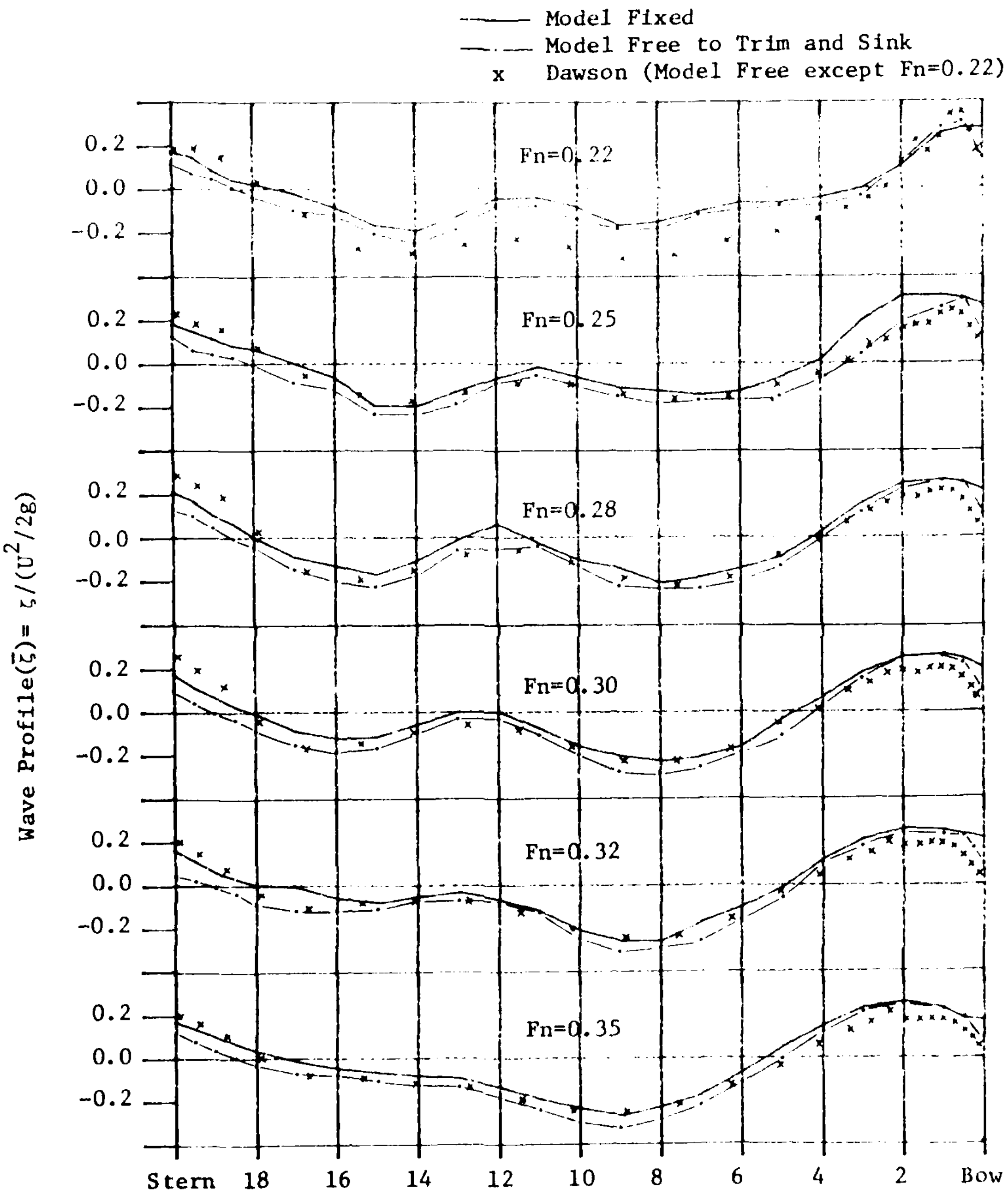

Figure 6 - Comparison of Calculated and Measured Wave Profiles for Model Series, C_B=0.60

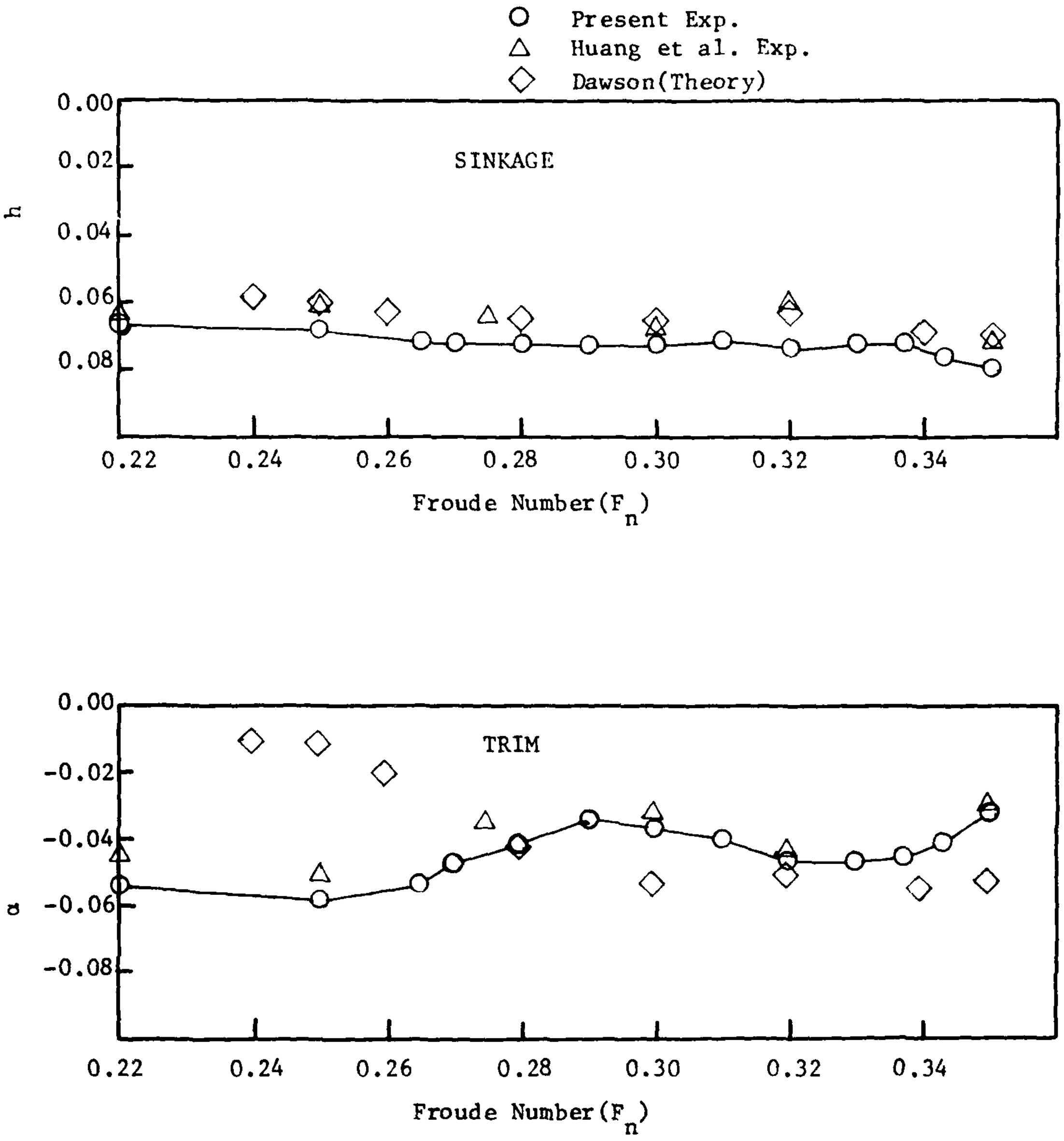

Figure 7 - Comparison of Sinkage and Trim

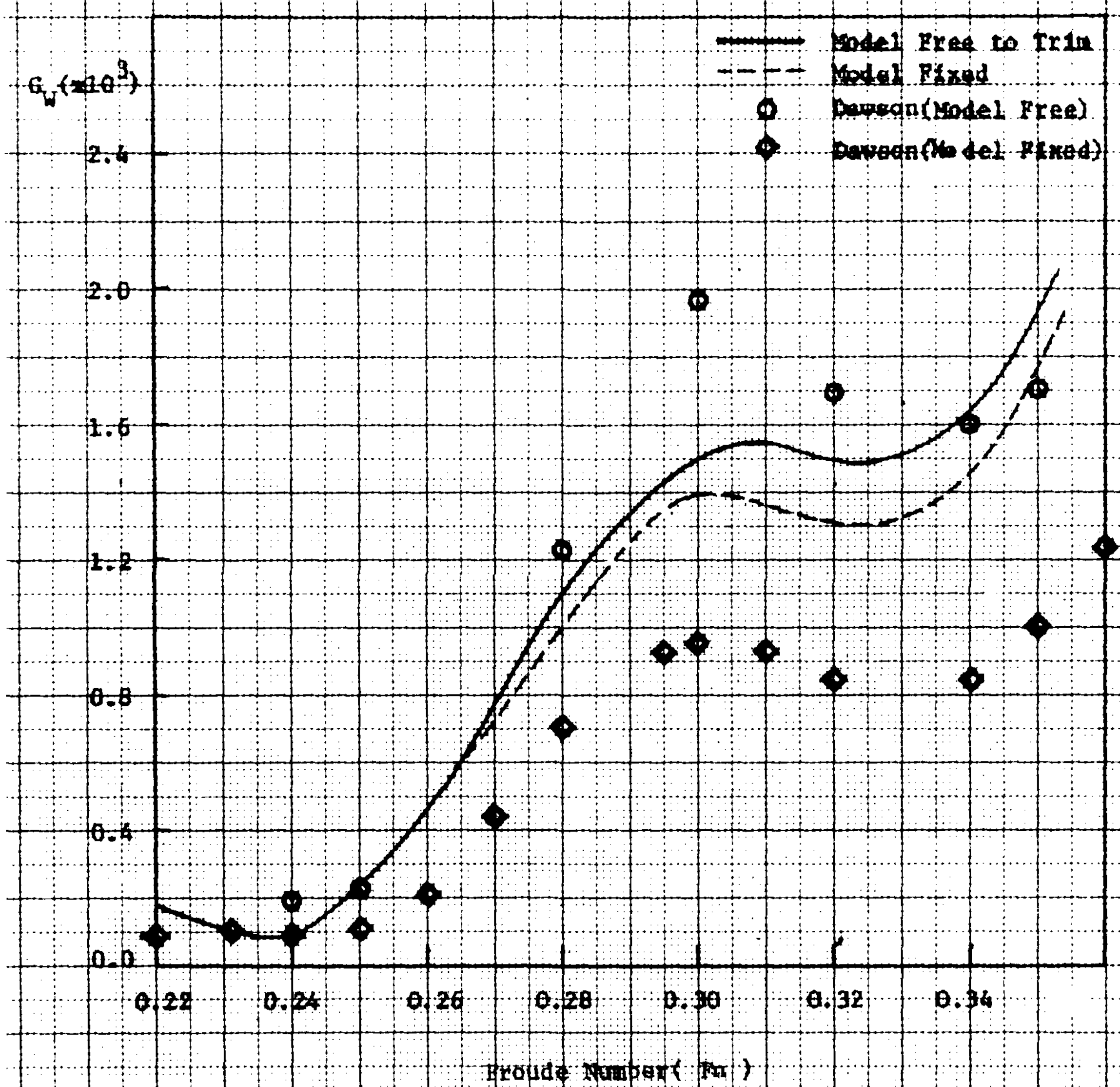

Figure 8 - Comparison of Wave Resistance Coefficients

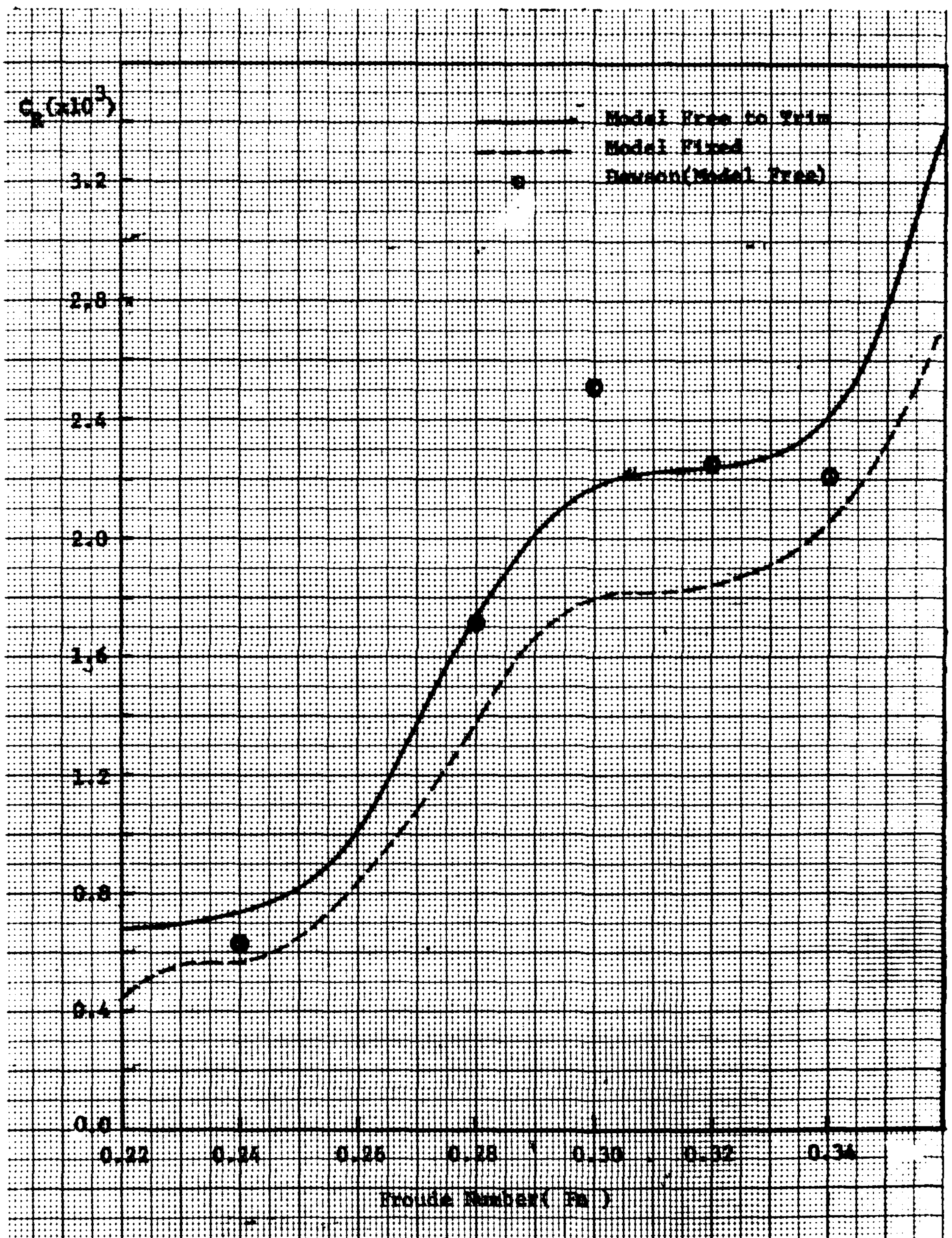

Figure 9 - Comparison of Residual Resistance Coefficients

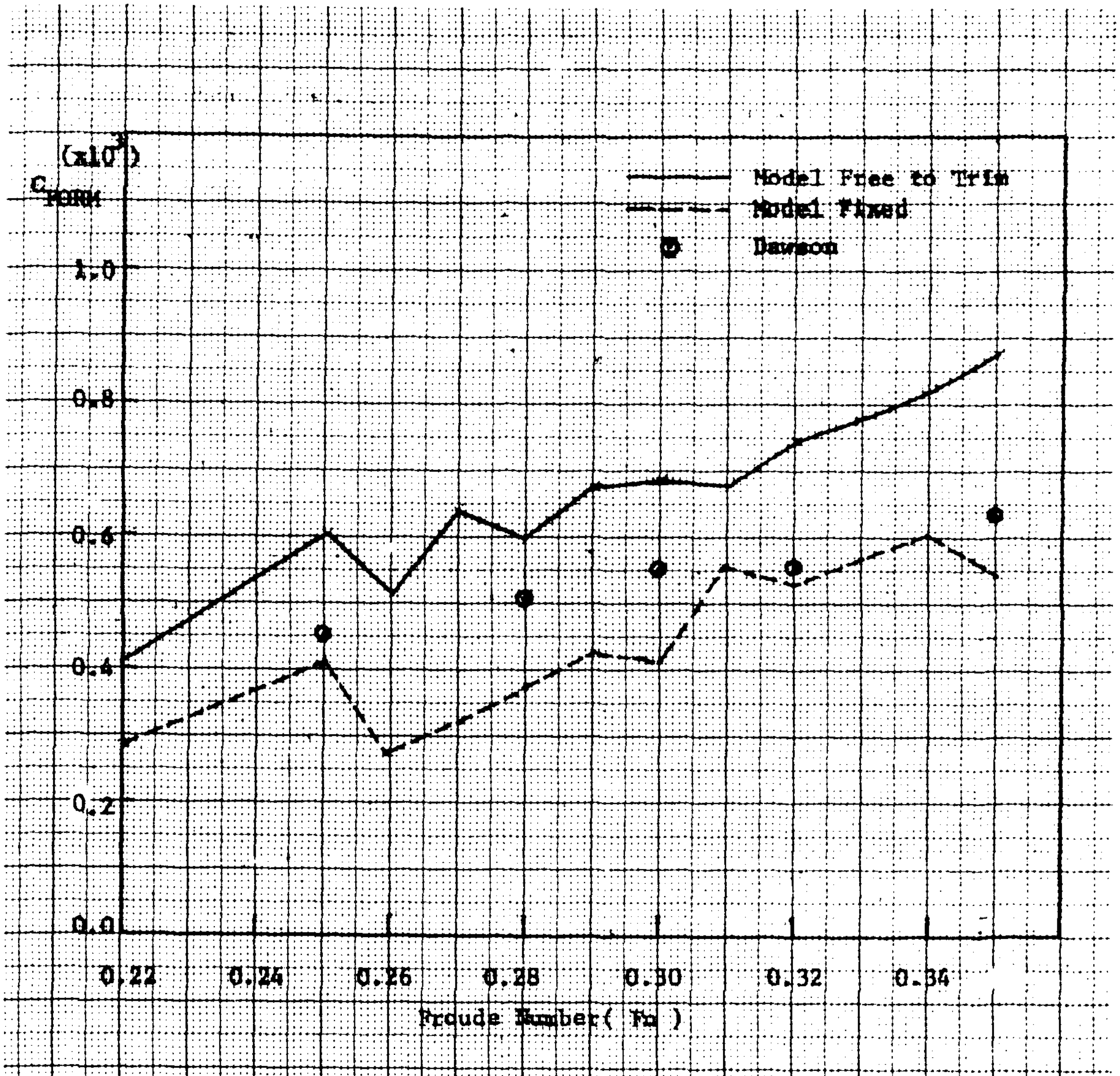

Figure 10 - Comparison of Form Drag Coefficients

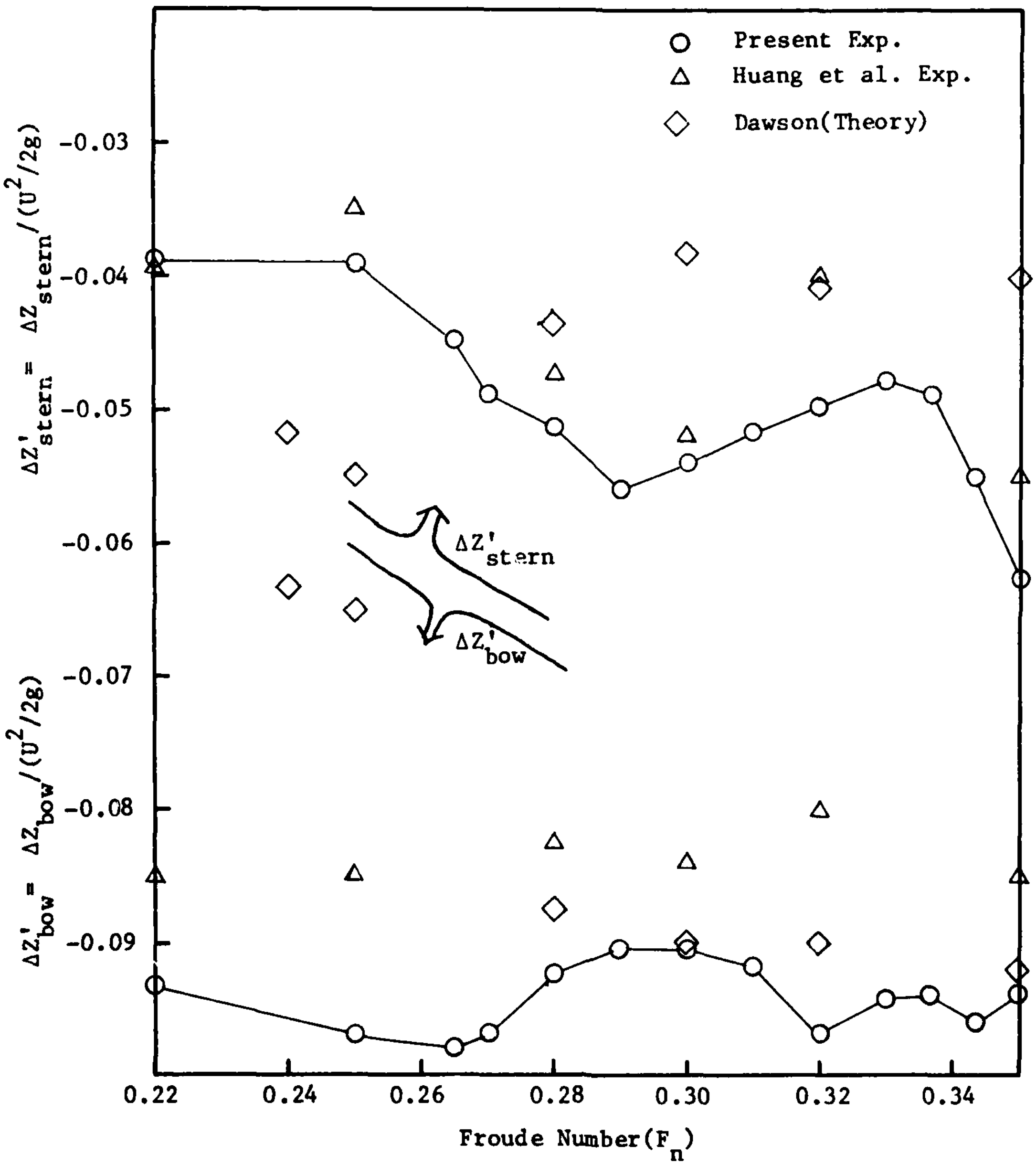

Figure 11 - Comparison of $\Delta Z'_{bow}$ and $\Delta Z'_{stern}$

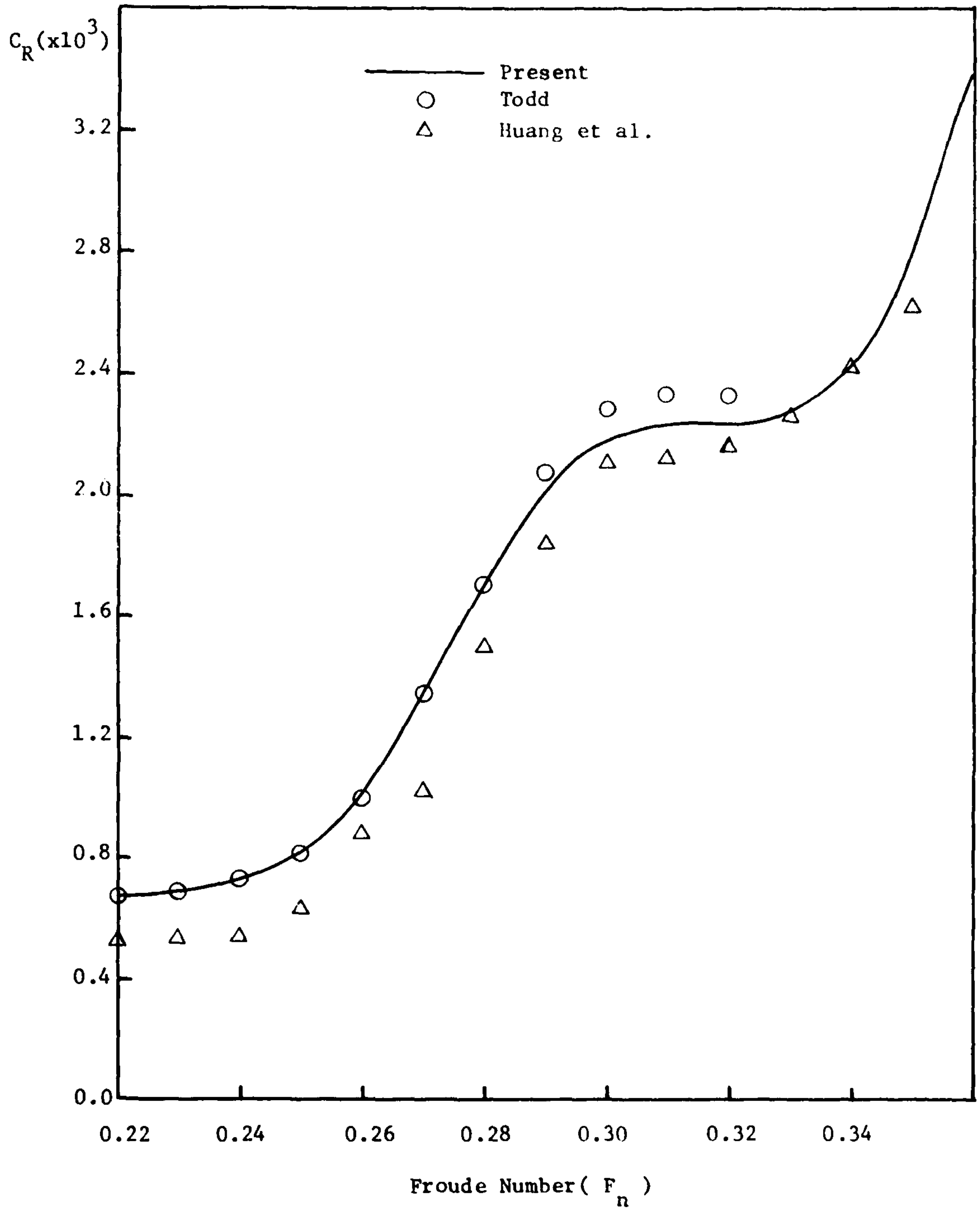

Figure 12 - Residual Resistance Coefficients

TABLE 1 - Particulars of Series 60, C_B=0.60
(from Todd, 1953)

L_{PP}	121.92 m (400.00 ft)
L_{WL}	123.96 m (406.70 ft)
B	16.25 m (53.33 ft)
Δ	7932.28 t (7807.0 ton)
C_B	0.60
C_X	0.977
C_P	0.614
C_W	0.706
$\frac{1}{2}\alpha_E$	7.00 degree
L/B	7.50
B/H	2.50
W.S.	2534.40 m^2 (27280.0 ft^2)

TABLE 2 — TABLE OF OFFSETS

SERIES 60, C_B = 0.60
(FROM TODD, 1953)

Half breadths of waterline given as fraction of maximum beam on each waterline

Model = 4210W (4287)
W.L. 1.00 is the designed load waterline

Forebody prismatic coefficient = 0.581
Afterbody prismatic coefficient = 0.646
Total prismatic coefficient = 0.614

		Waterlines							Area as fraction of max. area to
Sta.	Tan.	0.075	0.25	0.50	0.75	1.00	1.25	1.50	1.00 W.L.
FP	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.042	0.000
½	0.009	0.032	0.042	0.041	0.043	0.051	0.076	0.120	0.042
1	0.013	0.064	0.082	0.087	0.090	0.102	0.133	0.198	0.085
1½	0.019	0.095	0.126	0.141	0.148	0.160	0.195	0.278	0.135
2	0.024	0.127	0.178	0.204	0.213	0.228	0.270	0.360	0.192
3	0.055	0.196	0.294	0.346	0.368	0.391	0.440	0.531	0.323
4	0.134	0.314	0.436	0.502	0.535	0.562	0.607	0.683	0.475
5	0.275	0.466	0.589	0.660	0.691	0.718	0.754	0.804	0.630
6	0.469	0.630	0.733	0.802	0.824	0.841	0.862	0.889	0.771
7	0.666	0.779	0.854	0.906	0.917	0.926	0.936	0.946	0.880
8	0.831	0.898	0.935	0.971	0.977	0.979	0.981	0.982	0.955
9	0.945	0.964	0.979	0.996	1.000	1.000	1.000	1.000	0.990
10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
11	0.965	0.982	0.990	1.000	1.000	1.000	1.000	1.000	0.996
12	0.882	0.922	0.958	0.994	1.000	1.000	1.000	1.000	0.977
13	0.767	0.826	0.892	0.962	0.987	0.994	0.997	1.000	0.938
14	0.622	0.701	0.781	0.884	0.943	0.975	0.990	0.999	0.863
15	0.463	0.560	0.639	0.754	0.857	0.937	0.977	0.994	0.750
16	0.309	0.413	0.483	0.592	0.728	0.857	0.933	0.975	0.609
17	0.168	0.267	0.330	0.413	0.541	0.725	0.844	0.924	0.445
18	0.065	0.152	0.193	0.236	0.321	0.536	0.709	0.834	0.268
18½	0.032	0.102	0.130	0.156	0.216	0.425	0.626	0.769	0.187
19	0.014	0.058	0.076	0.085	0.116	0.308	0.530	0.686	0.109
19½	0.010	0.020	0.020	0.022	0.033	0.193	0.418	0.579	0.040
AP	0.000	0.000	0.000	0.000	0.000	0.082	0.270	0.420	0.004
Max half beam*	0.710	0.866	0.985	1.000	1.000	1.000	1.000	1.000	

*As fraction of maximum load waterline beam.

TABLE 3 - Wave Profiles($\bar{\zeta}$) with Model Fixed

STATN \ Fn	0.22	0.25	0.28	0.30	0.32	0.35
BOW	0.275	0.262	0.209	0.194	0.210	0.167
½	0.275	0.295	0.248	0.239	0.230	0.176
1	0.254	0.311	0.261	0.262	0.250	0.226
2	0.106	0.311	0.248	0.250	0.260	0.259
3	0.000	0.197	0.157	0.182	0.210	0.234
4	-0.042	0.016	0.026	0.068	0.120	0.151
5	-0.064	-0.066	-0.094	-0.034	-0.010	0.050
6	-0.064	-0.131	-0.144	-0.159	-0.100	-0.067
7	-0.106	-0.143	-0.183	-0.205	-0.170	-0.167
8	-0.148	-0.131	-0.209	-0.228	-0.260	-0.226
9	-0.169	-0.115	-0.144	-0.205	-0.260	-0.268
10	-0.085	-0.066	-0.105	-0.159	-0.210	-0.234
11	-0.042	-0.016	-0.026	-0.080	-0.120	-0.192
12	-0.042	-0.066	0.065	0.000	-0.070	-0.134
13	-0.127	-0.131	-0.013	0.000	-0.030	-0.092
14	-0.191	-0.196	-0.105	-0.057	-0.050	-0.084
15	-0.169	-0.196	-0.170	-0.114	-0.080	-0.067
16	-0.085	-0.066	-0.131	-0.125	-0.060	-0.050
17	-0.021	0.000	-0.091	-0.091	-0.	-0.017
18	0.021	0.006	0.000	-0.011	0.000	0.033
18½	0.042	0.082	0.065	0.023	0.030	0.067
19	0.085	0.115	0.105	0.068	0.060	0.100
19½	0.148	0.148	0.170	0.114	0.110	0.134
STERN	0.169	0.180	0.209	0.171	0.160	0.167

TABLE 4 - Wave Profiles($\bar{\zeta}$) for Model Free to Trim and Sink

STATN \ Fn	0.22	0.25	0.28	0.30	0.32	0.35
BOW	0.170	0.161	0.137	0.133	0.127	0.122
½	0.339	0.325	0.281	0.258	0.257	0.223
1	0.318	0.292	0.294	0.292	0.267	0.256
2	0.149	0.227	0.255	0.281	0.277	0.281
3	0.001	0.079	0.150	0.190	0.217	0.248
4	-0.042	-0.035	0.033	0.064	0.137	0.156
5	-0.042	-0.117	-0.098	-0.072	-0.023	0.030
6	-0.063	-0.134	-0.164	-0.152	-0.123	-0.079
7	-0.084	-0.134	-0.203	-0.220	-0.223	-0.179
8	-0.148	-0.150	-0.203	-0.254	-0.253	-0.246
9	-0.148	-0.117	-0.190	-0.243	-0.273	-0.288
10	-0.105	-0.068	-0.098	-0.163	-0.213	-0.263
11	-0.042	-0.019	-0.007	-0.072	-0.093	-0.204
12	-0.042	-0.052	-0.019	0.007	-0.043	-0.145
13	-0.143	-0.150	-0.020	0.007	-0.033	-0.095
14	-0.211	-0.199	-0.137	-0.061	-0.033	-0.087
15	-0.169	-0.199	-0.190	-0.129	-0.073	-0.070
16	-0.084	-0.085	-0.164	-0.152	-0.083	-0.045
17	-0.063	-0.052	-0.111	-0.118	-0.083	-0.037
18	0.000	0.030	-0.007	-0.050	-0.053	0.005
18½	0.043	0.063	0.033	-0.004	-0.003	0.039
19	0.085	0.079	0.085	0.030	0.027	0.072
19½	0.106	0.096	0.137	0.076	0.057	0.114
STERN	0.149	0.161	0.163	0.133	0.077	0.156

TABLE 5 - Sinkage and Trim

Fn	ΔZ_{bow} (cm)	ΔZ_{stern} (cm)	Sinkage	Trim
0.22	-1.402	-0.587	0.0663	0.0540
0.25	-1.882	-0.757	0.0681	0.0580
0.265	-2.131	-0.980	0.0715	0.0529
0.27	-2.187	-1.107	0.0719	0.0471
0.28	-2.245	-1.252	0.0720	0.0410
0.29	-2.360	-1.463	0.0727	0.0341
0.30	-2.530	-1.504	0.0723	0.0370
0.31	-2.736	-1.539	0.0711	0.0398
0.32	-3.076	-1.582	0.0734	0.0470
0.33	-3.183	-1.605	0.0711	0.0468
0.337	-3.312	-1.712	0.0714	0.0455
0.343	-3.500	-2.007	0.0753	0.0408
0.35	-3.574	-2.388	0.0785	0.0310

$$\text{Sinkage} = \frac{-(\Delta Z_{bow} + \Delta Z_{stern})}{U^2/g}$$

$$\text{Trim} = \frac{-(\Delta Z_{bow} - \Delta Z_{stern})}{U^2/2g}$$

TABLE 6 - Resistance, Model Fixed

Fn	C_T (10^{3})	C_F (10^{3})	C_R (10^{3})	C_W (10^{3})	Re (10^{7})
0.22	3.399	2.945	0.454	0.176	1.113
0.23	3.505	2.922	0.583	-	1.164
0.24	3.475	2.901	0.574	-	1.214
0.25	3.511	2.881	0.630	0.230	1.265
0.26	3.688	2.862	0.826	0.495	1.316
0.27	4.014	2.844	1.170	0.716	1.366
0.28	4.191	2.826	1.365	1.011	1.417
0.29	4.490	2.808	1.682	1.249	1.474
0.30	4.605	2.794	1.811	1.375	1.518
0.31	4.610	2.778	1.832	1.355	1.569
0.32	4.614	2.764	1.850	1.316	1.619
0.33	4.649	2.749	1.900	1.357	1.672
0.34	4.787	2.736	2.051	1.455	1.721
0.35	5.078	2.723	2.355	1.780	1.771

TABLE 7 - Resistance, Model Free to Trim

Fn	C_T (10^3)	C_F (10^3)	C_R (10^3)	C_W (10^3)	Re (10^7)
0.22	3.639	2.945	0.694	0.170	1.113
0.23	-	2.922	-	-	1.164
0.24	-	2.901	-	-	1.214
0.25	3.679	2.881	0.798	0.229	1.265
0.26	3.869	2.862	1.007	-	1.316
0.27	4.229	2.844	1.385	0.749	1.366
0.28	4.499	2.826	1.673	1.106	1.417
0.29	4.832	2.808	2.024	1.343	1.474
0.30	4.970	2.794	2.176	1.491	1.518
0.31	4.981	2.778	2.203	1.539	1.569
0.32	5.008	2.764	2.244	1.495	1.619
0.33	5.027	2.749	2.278	1.561	1.672
0.34	5.138	2.736	2.402	1.551	1.721
0.35	5.54	2.723	2.817	1.930	1.771

TABLE 8 - Residual Resistance Coefficients, $C_R(\times 10^{3})$

Fn	Todd	Huang	present
0.22	0.660	0.522	0.694
0.23	0.680	0.530	-
0.24	0.720	0.540	-
0.25	0.795	0.640	0.798
0.26	0.980	0.880	1.007
0.27	1.340	1.175	1.385
0.28	1.700	1.500	1.673
0.29	2.080	1.840	2.024
0.30	2.280	2.100	2.170
0.31	2.340	2.120	2.244
0.32	2.320	2.160	2.278
0.33	-	2.260	2.278
0.34	-	2.420	2.402
0.35	-	2.620	2.817

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